

VISIT...

LANZAROTE
Caliente.COM

Applications of Induction Motors

5.1 GENERAL DISCUSSION

The AC induction motor is used more than any other means to power industrial equipment. This is confirmed by the U.S. Department of Energy report on electric motors, which states that 53–58% of the electric energy generated is consumed by electric motors (see [Table 5.1](#)). Because there are so many applications, it is impossible to develop a list or guide for all the applications of AC induction motors.

However, a guide for the selection of three-phase induction motors for many applications had been developed and is shown in [Table 5.2](#). The table outlines the matching of the driven load requirements to the electric motor characteristics. In applying this guide, it must be recognized that the purpose of the horsepower ratings and NEMA standards for electric motors is to define the useful performance range of the motors in a way most intelligible to the user for fixed-frequency applications. For variable-frequency applications, see [Sec. 5.6](#) on motor selection for adjustable-frequency power supplies. The

TABLE 5.1 Electric Motor Population and Energy Consumption, 1977

Horsepower	No. of motors (000s)	New sales, average for 1973–1977 (000s)	Annual electric energy consumption, billions of kWh
1–5	54,583	3567	34
5.1–20	10,421	573	103
21–50	3,313	151	155
51–125	1,703	59	338
126 and over	<u>1,004</u>	<u>35</u>	<u>573</u>
Total	71,024	4385	1203

Source: U.S. Department of Energy Report DOE/CS-0147, 1980.

fixed-frequency rating of induction motors includes six major variables:

- Supply voltage and frequency
- Number of phases
- Rated horsepower
- Torque characteristics
- Speed
- Temperature

In addition, the basis of rating specifies the type of duty:

- Continuous duty
- Intermittent duty
- Varying duty

It is desirable to use standard motors for as many different applications as possible. Consequently, general-purpose continuous-rated motors should be used when

1. The peak momentary overloads do not exceed 75% of the breakdown torque
2. The root-mean-square (rms) value of the motor losses over an extended period of time does not exceed the losses at the service factor rating

TABLE 5.2 Three-Phase Electric Motor Selection Chart

For this type of equipment	Requiring these torques		With these load characteristics	Type and description ^a
	Starting	Max. running		
Water supply pumps Industrial and chemical pumps Cooling towers Air-handling equipment Compressors Conveyors Process machinery Petroleum and chemical process equipment	100–150% of full-load torque	200–250% of full-load torque	Continuous operation, constant speed, high speed (over 720 rpm), easy starting; subject to short time overloads; good speed regulation	<i>Energy-efficient:</i> NEMA design B, normal torques: normal starting current; can be used with variable-frequency/variable-voltage inverters; higher efficiency than standard design B motors
Centrifugal pumps Blowers and fans Drilling machines Grinders Lathes Compressors Conveyors	100–150% of full-load torque	200–250% of full-load torque	Variable load conditions, constant speed; subject to short time overloads; good speed regulation	<i>NEMA design B,</i> normal torques: normal starting current; can be used with variable-frequency/variable-voltage inverters

Reciprocating pumps Stokers Compressors Crushers Ball and rod mills	200–300% of full-load torque	Not more than full-load torque	High starting torque due to high inertia, back pressure, standstill friction, or similar mechanical conditions; torque requirements decrease during acceleration to full-load torque; not subject to severe overloads; good speed regulation	<i>NEMA design C</i> , high torque; normal starting current; not recommended for use with variable-frequency inverters
Punch presses Cranes Hoists Press brakes Shears Oil well pumps Centrifugals	Up to 300% of full-load torque	200–300% of full-load torque; loss of speed during peak loads required	Intermittent loads; may require frequent start, stop, and reverse cycles; machine uses a flywheel to carry peak loads; poor speed regulation to smooth power peaks; may require acceleration of high-inertia load	<i>NEMA design D</i> , high torque; high slip; standard types have slip characteristics of 5–8% or 8–13% slip

TABLE 5.2 Continued

For this type of equipment	Requiring these torques		With these load characteristics	Type and description ^a
	Starting	Max. running		
Blowers Fans Machine tools Mixing machines Conveyors Pumps	Some require low torque; others require several times full-load torque	200% of full-load torque at each speed	Speed selection is desired, and two, three, or four fixed speeds are sufficient; starting torque can be low on blowers to high on conveyors; metal-cutting machines are usually constant hp; friction loads (conveyors) are usually constant torque; fluid or air loads (blowers) are variable torque	<i>Multispeed</i> : general normal torque on dominant winding or speed; consequent pole windings or separate windings for each speed; based on load requirement, can be constant horsepower, constant torque, variable torque

Crushers	Can provide	200–300% of full-	Loads that -require	<i>Wound-rotor</i> : requires
Conveyors	torque up to	load torque	very high starting	rotor control system
Bending rolls	maximum		torque with low	to provide desired
Ball and rod	torque at		starting current;	characteristic; control
mills	standstill		require speed	may be resistors or
Centrifugal blowers			adjustment over	reactors or fixed-
Pumps			limited range	frequency inverters
Printing presses			(2 to 1); torque	in the secondary
Cranes and			control during	(rotor) circuit; actual
hoists			acceleration or	load speed depends
Centrifugalsl			controlled	on setting of rotor
			acceleration	control

^a See [Chapter 1](#) for a detailed description.

3. The duration of any overload does not raise the momentary peak temperature above a value safe for the motor's insulation system

5.1.1 Energy-Efficient Motors

The selection of an energy-efficient motor should be based on several additional factors:

1. Electric power-saving and life-cycle cost comparison to standard motors
2. Improved ability to perform under adverse conditions such as abnormal voltage (See Secs. 5.3 and 5.4 for performance comparisons to standard motors. Note the superior performance of energy-efficient motors under abnormal voltage conditions.)
3. Lower operating temperatures
4. Noise level
5. Ability to accelerate higher-inertia loads than standards motors
6. Higher operating efficiencies at all load points. (Figure 5.1 illustrates this comparison on a 25-hp, 1765-rpm polyphase induction motor. Note that at all loads the energy-efficient motor presents an opportunity for energy savings.)

In general, energy-efficient motors can be justified on a payback basis because of the annual saving of electric energy. This saving is a function of the hours of operation per year and kilowatt-energy reduction. For example, consider a 25-hp, 1800-rpm application with an average annual operating time of 4000 hr and a cost of electric power of 5¢/kWh:

Standard motor efficiency = 88%

$$\text{Power input} = \frac{25 \times 0.746}{0.88} = 21.19 \text{ kW}$$

Energy-efficient motor efficiency = 93.0%

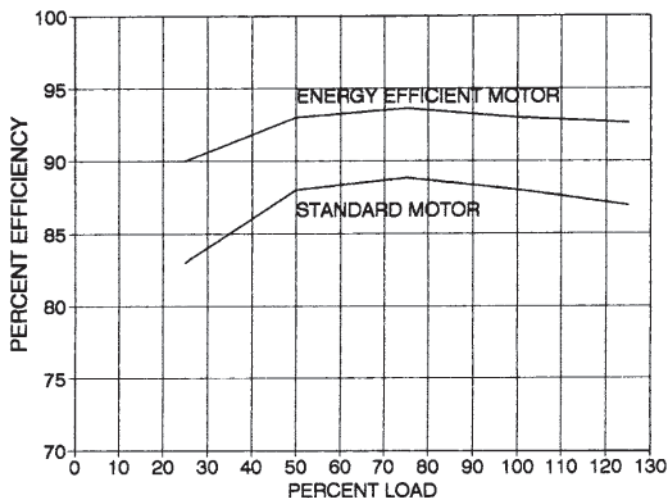


FIGURE 5.1 Comparison of the operating efficiency of energy-efficient versus standard polyphase induction motors at 25 hp and 1765 rpm.

$$\text{Power input} = \frac{25 \times 0.746}{0.93} = 20.05 \text{ kW}$$

$$\begin{aligned} \text{Annual energy saving} &= (21.19 - 20.05) \times 4000 \\ &= 4560 \text{ kWh} \end{aligned}$$

$$\text{Annual power cost saving} = 4560 \times 0.05 = \$228$$

$$\text{Typical list price standard drip-proof motor} = \$993$$

$$\begin{aligned} \text{Typical list price energy-efficient, drip-proof motor} \\ &= \$1226 \end{aligned}$$

$$\text{Time to recover initial cost} = \frac{1226 - 993}{228} = 12 \text{ months}$$

thus indicating a very favorable cost/benefit ratio for this application.

This method of cost/benefit analysis is approximate but is generally acceptable if the time to recover the initial investment is less than 3 yr. However, when it is desirable, more accurate methods can be used that consider the increasing cost of power, the required return on the investment, and the product useful life. The detailed procedures for making this type of economic analysis are described in [Chapter 7](#).

In certain applications and duty cycles, energy-efficient motors cannot be justified on the basis of energy saved; for example:

1. Intermittent-duty or special torque applications:
 - Hoists and cranes
 - Traction drives
 - Punch presses
 - Machine tools
 - Oil field pumps
 - Fire pumps
 - Centrifugals
2. Types of loads:
 - Multispeed
 - Frequent starts and stops
 - Very high-inertia loads
 - Low-speed motors (below 720 rpm)

Additional factors that should be considered in the selection and applications of electric motors are reviewed in the following sections of this chapter.

5.2 VARYING DUTY APPLICATIONS

In many applications, the load imposed on the driving motor varies from no load to a peak load. When the motor load fluctuates, the temperature rise of the motor fluctuates. When there is a definite repeated load cycle, the motor size selection can be based on the rms value of motor losses for the load cycle. However, normally, the losses at each increment of the load cycle are not available to the user. Therefore, a good approximation for the motor size selection can be based on the rms horsepower for the load cycle. The rms horsepower is then defined as that equivalent steady-state horsepower

that would result in the same temperature rise as that of the defined load cycle. When making the rms calculation, it is assumed that, when the motor is running, the heat dissipation is 100% effective. However, when the motor is at standstill, the heat dissipation is severely reduced and is limited to dissipation by radiation and natural convection. This can be compensated for by using an effective cooling time at standstill of one-fourth of the total standstill time. *An important word of caution:* This method of selecting electric motors is not satisfactory for applications requiring frequent starting or plug reversing or systems with a high load inertia.

5.2.1 Sample Calculation

Duty cycle	
40 hp	15 min
20 hp	20 min
10 hp	5 min
Stop	5 min
Total cycle	45 min

$$\text{hp}^2 \times t = 40^2 \times 15 = 24,000$$

$$20^2 \times 20 = 8,000$$

$$10^2 \times 5 = 500$$

$$0 \times 5 = 0$$

$$\text{hp}^2 \times t \text{ total} = 32,500$$

$$T_e = \text{effective cooling time} = 15 + 20 + 5 + 1/4 \times 5$$

$$= 41.25 \text{ min}$$

$$\text{rms hp} = \sqrt{\frac{\text{hp}^2 \times t}{T_e}} = \sqrt{\frac{32,500}{41.25}} = 28 \text{ hp}$$

From a thermal standpoint, a 30-hp standard motor would be satisfactory for this application.

Is the ratio of peak horsepower to nameplate (NP) horsepower satisfactory?

$$\frac{\text{Peak hp}}{\text{NP hp}} = \frac{40}{30} \times 100 = 133\%$$

Based on a limit of 150% for the ratio of peak horsepower to motor nameplate horsepower, the 30-hp motor could be satisfactory for this load.

Consider a slightly different cycle:

Duty cycle	
40 hp	10 min
20 hp	25 min
10 hp	10 min
Total cycle	45 min

$$40^2 \times 10 = 16,000$$

$$20^2 \times 25 = 10,000$$

$$10^2 \times 10 = 1,000$$

$$\text{hp}^2 \times \text{total} = 27,000$$

$$\text{Effective cooling time} = 10 + 25 + 10 = 45 \text{ min}$$

$$\text{rms hp} = \sqrt{\frac{27,000}{45}} = 24.5 \text{ hp}$$

From a thermal standpoint, a standard 25-hp motor would be satisfactory. However,

$$\frac{\text{Peak hp}}{\text{NP hp}} = \frac{40}{25} \times 100 = 160\%$$

Based on a limit of 150% for this ratio, the use of a 25-hp motor is not considered satisfactory, and a 30-hp motor should be used.

5.3 VOLTAGE VARIATION

NEMA Standard MG1 recognizes the effect of voltage and frequency variation on electric motor performance. The standard recommends that the voltage deviation from the motor rated voltage not exceed $\pm 10\%$ at the rated frequency. A certain degree of confusion may exist in regard to the rated motor voltage since the rated motor voltage and the system voltage are different. The rated motor voltage has been selected to match the utilization voltage available at the motor terminals. This voltage allows for the voltage drop in the power distribution system and for voltage variation as the system load changes.

The basis of the NEMA standard rated motor voltages for three-phase, 60-Hz induction motors is as follows:

System voltage	Rated motor voltage
208	200
240	230
480	460
600	575

For single-phase, 60-Hz induction motors, the basis for standard rated motor voltages is as follows:

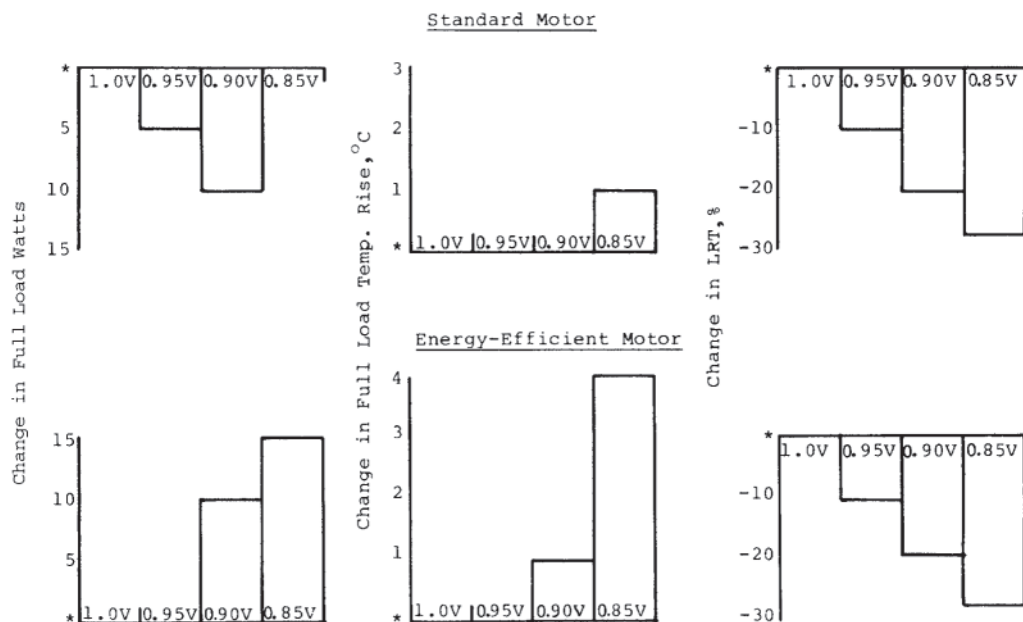
System voltage	Rated motor voltage
120	115
240	230

Polyphase induction motors are designed to operate most effectively at their nameplate rated voltage. Most motors will operate satisfactorily over $\pm 10\%$ voltage variation, but deviations from the nominal motor design voltage can have marked effects on the

TABLE 5.3 Effect of Voltage Variation on Polyphase Induction Motor Performance

Operating characteristic	Effect of voltage change		
	90% voltage	110% voltage	120% voltage
Starting and maximum running torque	Decrease 19%	Increase 21%	Increase 44%
Synchronous speed	No change	No change	No change
Percent slip	Increase 23%	Decrease 17%	Decrease 30%
Full-load speed	Decrease 1%	Increase 1%	Increase 1%
Starting current	Decrease 10–12%	Increase 10–12%	Increase 25%
Magnetic noise, any load	Decrease slightly	Increase slightly	Noticeable increase
<i>Standard NEMA design B motors</i>			
Efficiency			
Full load	Increase 0.5–1%	Decrease 1–4%	Decrease 7–10%
3/4 load	Increase 1–2%	Decrease 2–5%	Decrease 6–12%
1/2 load	Increase 2–4%	Decrease 4–7%	Decrease 14–18%
Power factor			
Full load	Increase 8–10%	Decrease 10–15%	Decrease 10–30%

3/4 load	Increase 10–12%	Decrease 10–15%	Decrease 10–30%
1/2 load	Increase 10–15%	Decrease 10–15%	Decrease 15–40%
Full-load current	Increase 1–5%	Increase 2–11%	Increase 15–35%
Temperature rise at full load	Increase 6–12%	Increase 4–23%	Increase 30–80%
<i>Energy-efficient NEMA B motors</i>			
Efficiency			
Full load	Decrease 1–2%	Increase 0.5–1%	Small increase
3/4 load	Minimal change	Minimal change	Decrease 0.5–2%
1/2 load	Increase 1–2%	Decrease 1–2%	Decrease 7–20%
Power factor			
Full load	Increase 1%	Decrease 3%	Decrease 5–15%
3/4 load	Increase 2–3%	Decrease 4%	Decrease 10–30%
1/2 load	Increase 4–5%	Decrease 5–6%	Decrease 10–30%
Full-load current	Increase 11%	Decrease 7%	Decrease 11%
Temperature rise at full load	Increase 23%	Decrease 14%	Decrease 21%



*Rating Point: Full-Load Watts, Full-Load Temperature Rise, and LRT at 100% Voltage

FIGURE 5.2 Comparison of the effects of low voltage on the performance of three-phase standard and energy-efficient motors at 1 hp and 1750 rpm.

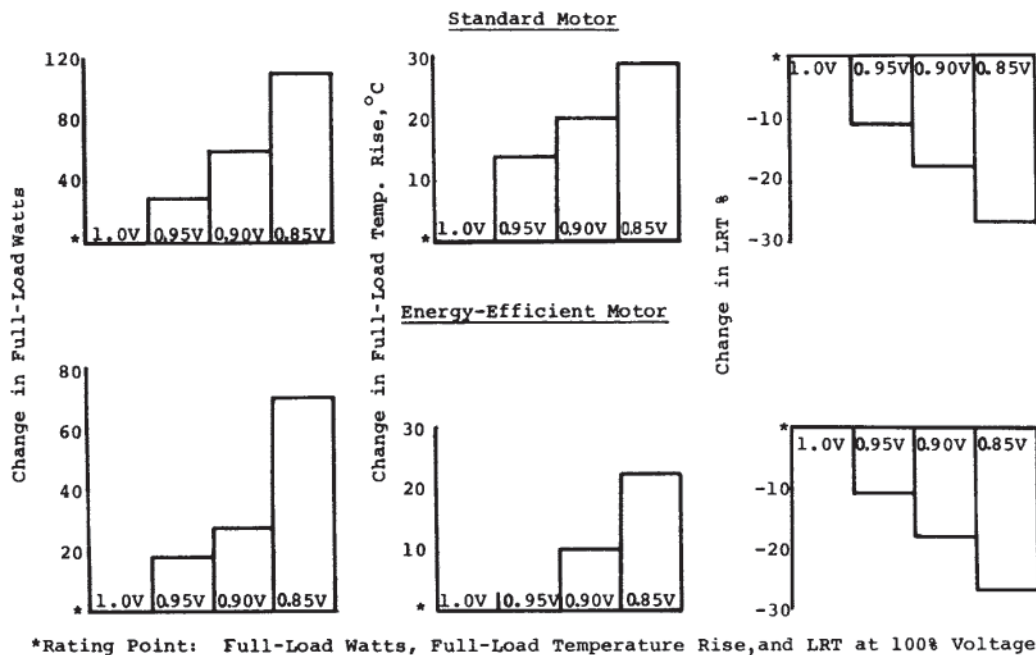


FIGURE 5.3 Comparison of the effects of low voltage on the performance of three-phase standard and energy-efficient motors at 5 hp and 1750 rpm.

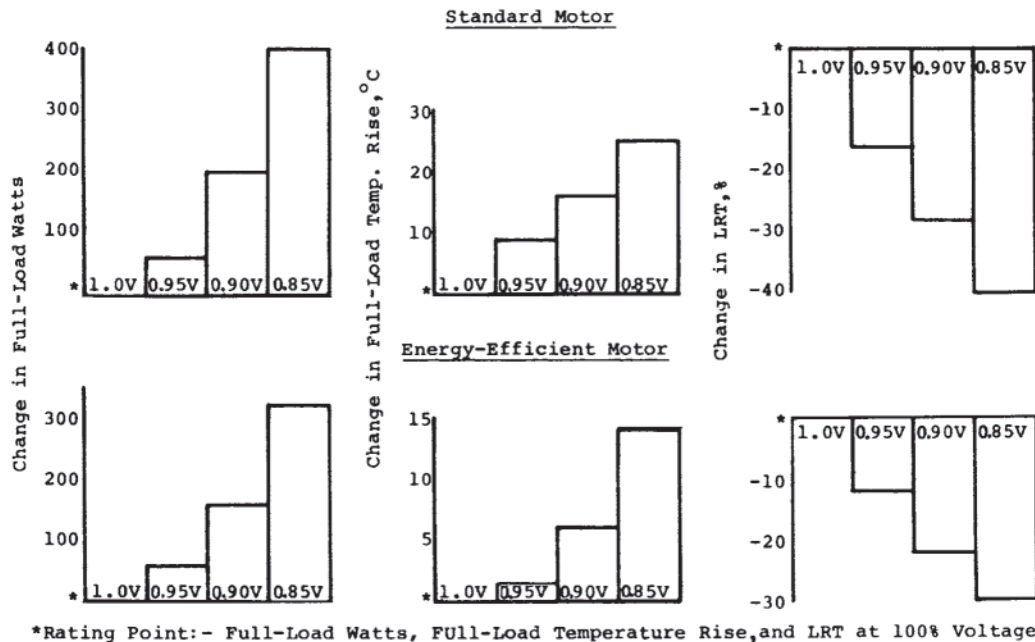


FIGURE 5.4 Comparison of the effects of low voltage on the performance of three-phase standard and energy-efficient motors at 25 hp and 1750 rpm.

motor performance. Table 5.3 indicates the type of changes in performance to expect with variation in the motor terminal voltage. The table shows the effect on the efficiency and power factor in standard NEMA design B motors and also in energy-efficient motors. It is important to note that the efficiency and the power factor of energy-efficient motors are not as sensitive to voltage variations as standard motors.

In recent years, the trend in some areas is to decrease system voltage to reduce the system load. In some cases, this reduction has been as low as 85% of the nominal voltage. For most electric motor loads, this increases rather than decreases the electric motor input and increases the full-load temperature rise. Also, the locked-rotor torque is severely reduced such that hard-to-start loads may not start at the 85% voltage level. Figures 5.2–5.4 illustrate the effect of reduced voltage on selected horsepower ratings of both standard motors and energy-efficient motors.

5.4 VOLTAGE UNBALANCE

Voltage unbalance can be more detrimental than voltage variation to motor performance and motor life. When the line voltages applied to a polyphase induction motor are not equal in magnitude and phase angle, unbalanced currents in the stator windings will result. A small percentage voltage unbalance will produce a much larger percentage current unbalance.

Some of the causes of voltage unbalance are the following:

1. An open circuit in the primary distribution system.
2. A combination of single-phase and three-phase loads on the same distribution system, with the single-phase loads unequally distributed.
3. An open wye-delta system.
 - a. Variation in ground supply impedance: An increase in primary ground impedance increases the voltage and current unbalances. Maximum unbalance occurs with overloaded transformers, and the large single-phase load is in the lagging phase. The motor serves to balance the

- system voltage better when the motor is loaded than when it is unloaded.
- b. Transformer loading varied 50 to 150%: The greatest unbalance occurs when a smaller transformer is lightly loaded and a larger transformer is overloaded. If a single-phase load varies over a large range, it is better to supply this phase with the larger transformer on the leading phase.
 - c. Impedance of lines to the single-phase loads: The voltage and current unbalance ratios increase with the line impedances. Again, the unbalance ratios decrease as the motor is loaded more heavily.
 - d. Impedance of the supply line to the motor: The voltage and current unbalance ratios decrease with an increase in the line impedance to the motor. However, this results in lower voltage at the motor and decreased motor torque and speed.
 - e. Other parameters: Variations in the magnitude of transformer impedances, the power factor of single-phase loads, and primary line impedances have minor effects (not more than 3%) on the phase currents and unbalance ratios.
4. An open delta-delta system: When the two transformers are supplied by three-phase conductors, the only difference is in the lack of neutral impedance. Therefore, under usual conditions, the open delta-delta configuration will show superior performance to the open wye-delta configuration. However, when there are unequal line impedances or unusually long supply lines, there are additional observations.
- a. There are mixed effects with variation of the lines supplying the single-phase loads.
 - b. An increase in the common primary supply line impedance results in increased voltage and current unbalances.

The unbalanced line voltages introduce negative sequence voltages in the polyphase motor. This negative sequence voltage produces an air gap flux rotating in a direction opposite to the rotor, thus producing high currents in the motor. A small negative sequence voltage can produce motor currents considerably in excess of those present under balanced voltage conditions.

NEMA Standard MG1 defines the percent voltage unbalance as follows:

$$\text{Percent voltage unbalance} = 100 \times \frac{\text{maximum voltage deviation from average voltage}}{\text{average voltage}}$$

These unbalanced voltages will result in unbalanced currents on the order of 6 to 10 times the voltage unbalance. Consequently, the temperature rise of the motor operating at a particular load and voltage unbalance will be greater than for the motor operating under the same conditions with balanced voltages. In addition, the large unbalance of the motor currents will result in nonuniform temperatures in the motor windings. An example of the effect of unbalanced voltages on performance is illustrated in [Table 5.4](#) for a 5-hp motor.

Voltages should be evenly balanced as closely as possible. *Operation of a motor above 5% voltage unbalance is not recommended.* Even at 5% voltage unbalance, motor current unbalance on the order of 40% can exist.

In recognizing the detrimental effect of unbalanced line voltage on electric motor performance, NEMA Standard MG1 recommends derating motors that are applied to unbalanced systems, in accordance with [Fig. 5.5](#) (NEMA MG1-14.35):

When the derating factor is applied, the selection and setting of the overload device should take into account the combination of the derating factor applied to the motor and the increase in current resulting from the unbalanced voltages. This is a complex problem involving the variation in motor current as a function of load and voltage unbalance in addition to the characteristics of the overload device relative to I_{maximum} or I_{average} . In the absence of specific information, it is recommended that

TABLE 5.4 Effect of Voltage Unbalance on Motor Performance^a

Characteristic	Performance		
	230	230	230
Average voltage	230	230	230
Percent unbalanced voltage	0.3	2.3	5.4
Percent unbalanced current	0.4	17.7	40.0
Increased temperature rise, °C	0	30	40

^a5-hp, 1725-rpm, 230-V, three-phase, 60-Hz motor.

overload devices be selected and/or adjusted at the minimum value that does not result in tripping for the derating factor and voltage unbalance that applies. When unbalanced voltages are anticipated, it is recommended that the overload devices be selected so as to be responsive to I_{maximum} in preference to overload devices responsive to I_{average} .*

The order of magnitude of the current unbalance is influenced not only by the system voltage unbalance but also by the system impedance, the nature of the loads causing the unbalance, and the operating load on the motor. Figure 5.6 indicates the range of unbalanced currents for various motor load conditions and system voltage unbalance.

The effect on other electric motor characteristics can be summarized as follows:

1. *Torques.* The locked-rotor and breakdown torques are decreased. If the voltage unbalance should be extremely severe, the torques might not be adequate for the application.
2. *Full-Load Speed.* The full-load speed is reduced slightly.

* Reprinted by permission from NEMA Standard Publication No. MG1-1987, *Motors and Generators*, copyright 1987 by the National Electrical Manufacturers Association.

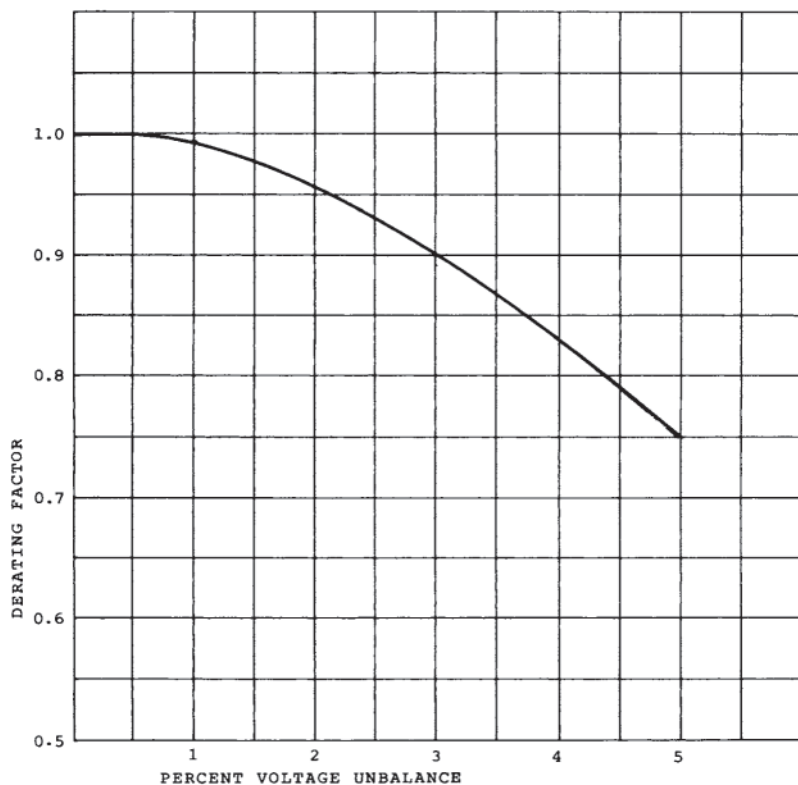


FIGURE 5.5 Derating factor for unbalanced voltages on polyphase induction motors. (Reprinted by permission from NEMA Standards Publication No. MG1-1987, *Motors and Generators*, copyright 1987 by the National Electrical Manufacturers Association.)

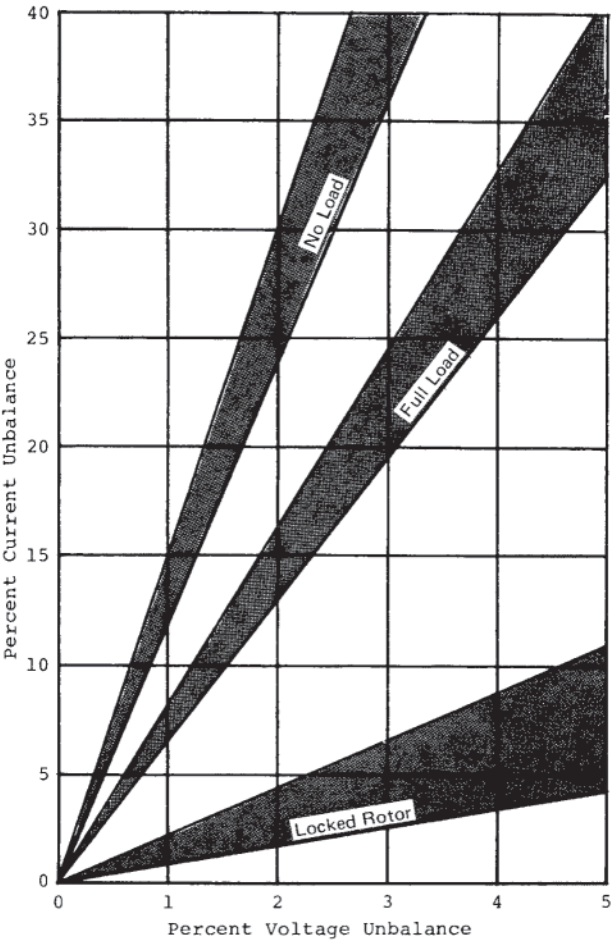


FIGURE 5.6 Effect of voltage unbalance on polyphase induction motor currents.

3. *Locked-Rotor Current.* The locked-rotor current will be unbalanced to the same degree that the voltages are unbalanced, but the locked-rotor kilovolt-amperes will increase only slightly.
4. *Noise and Vibration.* The unbalanced voltages can cause an increase in noise and vibration. Vibration can be particularly severe on 3600-rpm motors.

5.5 OVERMOTORING

In many instances, the practice has been to overmotor an application, i.e., to select a higher-horsepower motor than necessary. The disadvantages of this practice are

- Lower efficiency
- Lower power factor
- Higher motor cost
- Higher controller cost
- Higher installation costs

One example of overmotoring is illustrated by the case of the varying duty applications discussed in Sec. 5.2. Consider the comparisons of the 40-hp motor that could have been selected based on the peak load versus the 30-hp motor that can be selected on the basis of the duty cycle:

1. Motor cost: list price of standard open 1800-rpm drip-proof motor:
 - 30 hp = \$1160
 - 40 hp = \$1446
2. Control Cost: NEMA-1 general-purpose motor, 240-V starter:
 - 30 hp, size 3 = \$600
 - 40 hp, size 4 = \$1350

This results in a cost difference of \$1036, or 59%.

Figure 5.7 shows the difference in the input watts and Fig. 5.8 the difference in the input kilovolt-amperes for 30- and 40-hp motors

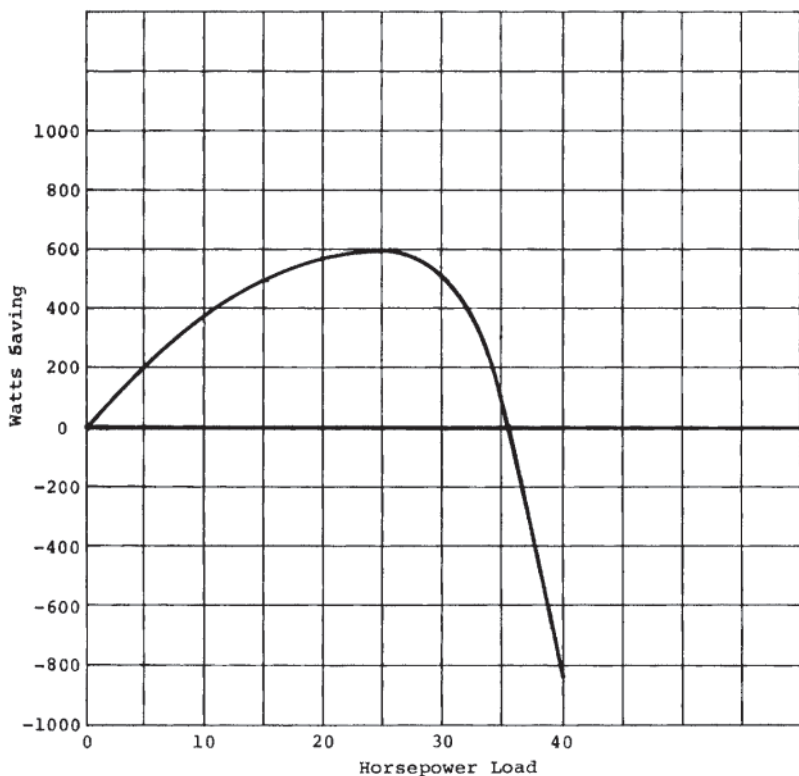


FIGURE 5.7 Power savings in watts for a 30-hp motor versus a 40-hp motor at the same load.

operating at the same output. At loads above 36 hp, the input is more favorable for the 40-hp motor. However, at loads below 36 hp, the kilowatt and kilovolt-ampere inputs are lower with the 30-hp motor.

In general, the larger the difference between the actual load and the motor rating, the higher the input requirements for the same load.

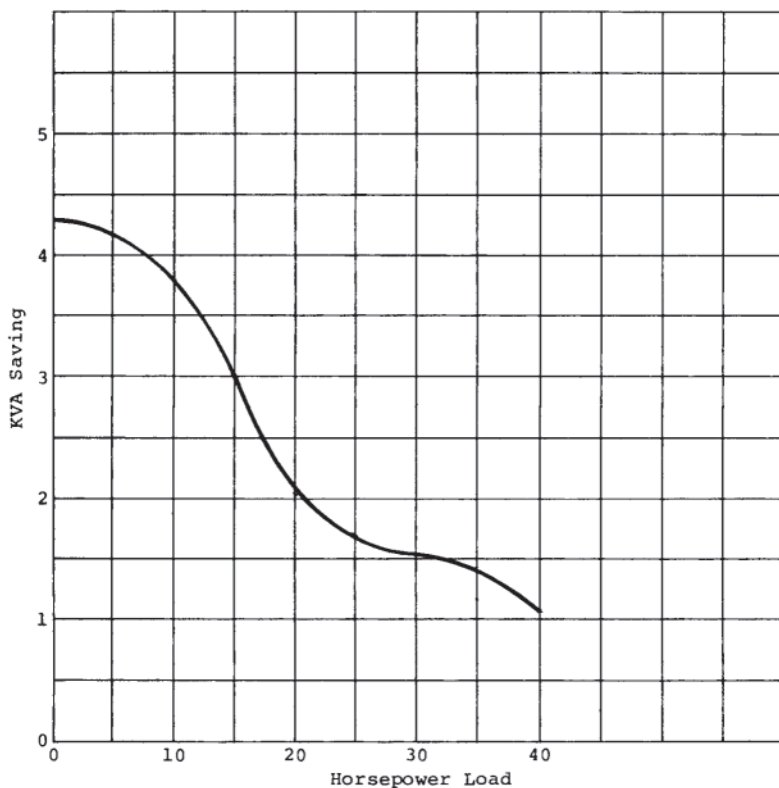


FIGURE 5.8 Savings in kilovolt-amperes for a 30-hp motor versus a 40-hp motor at the same load.

5.6 POLYPHASE INDUCTION MOTORS SUPPLIED BY ADJUSTABLE-FREQUENCY POWER SUPPLIES

When applying polyphase induction motors to adjustable-frequency power supplies, it must be remembered that the induction motor nameplate rating is based on a fixed-frequency, fixed-voltage, sine-wave voltage source. Therefore, the application of polyphase

induction motors with adjustable-frequency power supplies requires consideration of additional features that are not considered for fixed-frequency motor applications.

5.6.1 Types and Characteristics of Loads

Most electric motor loads fall in one of the following categories:

- Variable-torque loads
- Constant-torque loads
- Constant-horsepower loads
- Cyclical, intermittent, or varying loads

Variable-Torque Loads. For this type of load, the torque usually increases as the square of the speed, and the horsepower increases as the cube of the speed. This type of load is typical of fans and centrifugal pumps within their normal operating range. The characteristic of a variable-torque load is illustrated in Fig. 5.9. The

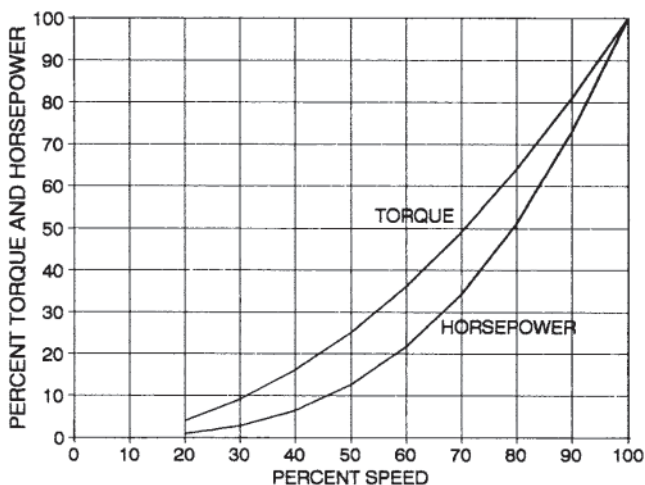


FIGURE 5.9 Load characteristics for variable-torque loads.

selection of the induction motor horsepower rating when supplied by a non-sine-wave power source for a variable-torque load can be based on the following:

- Standard motor, derated to 85 or 90% of nameplate horsepower rating
- Standard motor with 1.15 service factor, no derating
- Energy-efficient motor, no derating

Since the horsepower required by the variable-torque load increases as the cube of the driven speed, the motor will be overloaded if it is operated above its base speed.

Constant-Torque Loads. The motor torque required for this type of load is constant over the operating range and is not a function of speed. The motor horsepower required is proportional to the output speed. Typical constant-torque loads are conveyors, cranes, positive-displacement pumps, and mixers. The characteristic of this type of load is illustrated in Fig. 5.10. The selection of the motor horsepower

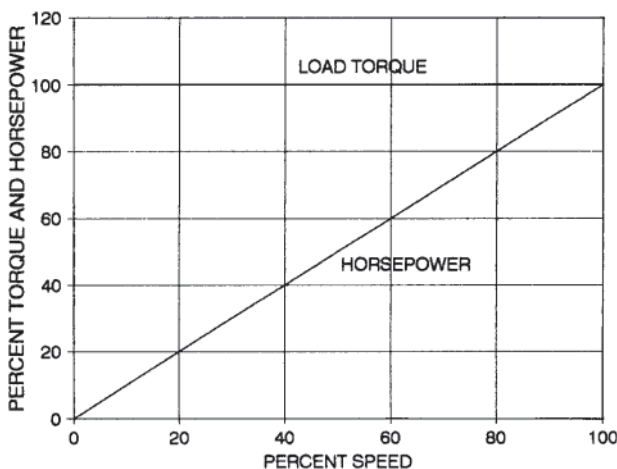


FIGURE 5.10 Load characteristics for constant-torque loads.

rating for constant-torque loads depends on the speed range of continuous operation.

1. For 2-to-1 speed range (i.e., 60–30 Hz) continuous operation:
 - a. Standard motors derated 85–90% of nameplate horsepower
 - b. Standard motors, class F insulation, 1.15 service factor, no derating
 - c. Energy-efficient motors, no derating
2. For 6-to-1 speed range continuous operation (i.e., 60–10 Hz):
 - a. Standard motors, increase up to two sizes over the base horsepower required.
 - b. Standard motors, class F insulation, 1.15 service factor, increase up to one size over base horsepower required.
 - c. Energy-efficient motors, increase up to one size over base horsepower required.
 - d. For operation below 10 Hz, special cooling for the motor usually required.
 - e. For more specific information, consult the motor manufacturer and the inverter manufacturer.

Constant-Horsepower Loads. For a constant-horsepower load, the load torque decreases as the speed increases, and the horsepower required remains essentially constant. This type of load is typical of metal-cutting machinery operating at a constant cutting or grinding velocity. As the diameter of the work is decreased, the drive speed is increased to maintain constant cutting velocity. The operating range is above base speed (i.e., 60 Hz and higher); therefore, the induction motor base speed must be selected so that at the maximum operating speed, the safe operating speeds of the induction motor and the driven equipment are not exceeded. The motor manufacturer and the equipment manufacturer should be consulted to determine the maximum safe speed for the system. These types of drives generally operate at a fixed voltage above base speed rather than constant

volts/hertz. It must be determined that the induction motor will develop the horsepower required over the speed range required. Figure 5.11 shows the operating capability of a 10-hp standard induction motor in the constant-horsepower range (i.e., 60–120 Hz), and Fig. 5.12 illustrates the load characteristic for a constant-horsepower load.

Cyclical and Intermittent Loads. These types of loads require special consideration in sizing both the induction motor and the adjustable-frequency power supply. The motor manufacturer and the adjustable-frequency power supply manufacturer should be consulted for these types of applications.

5.6.2 Characteristics of an Induction Motor Operating on an Adjustable-Frequency Power Supply

Induction Motor Torques. The polyphase induction motor has a unique speed-torque curve at each frequency when operated at constant volts/hertz. This family of speed-torque curves is illustrated

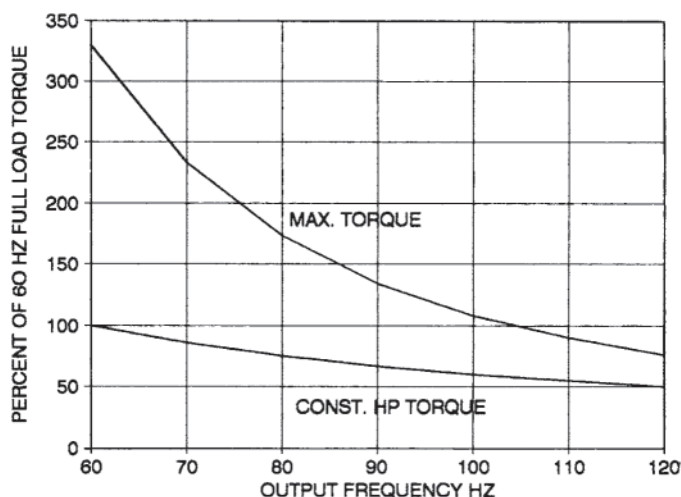


FIGURE 5.11 Performance of a 10-hp induction motor in the constant-horsepower range.

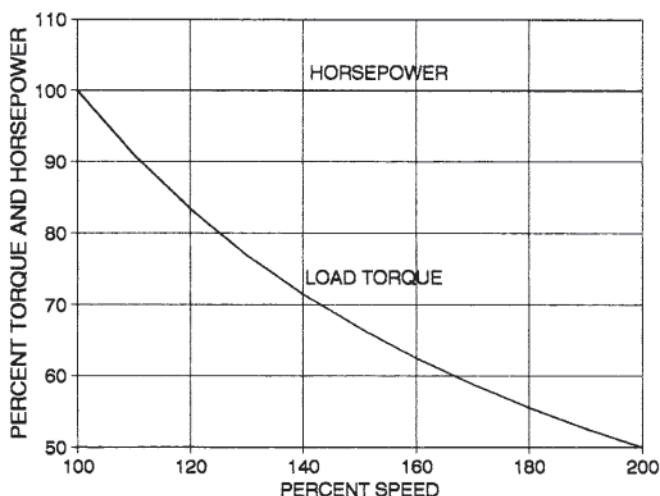


FIGURE 5.12 Load characteristics for constant-horsepower loads.

in Fig. 5.13 for a 100-hp, 1800-rpm, energy-efficient induction motor. The utilization of the motor torque capability depends on the current restriction imposed by the adjustable-frequency power supply. In most cases, the power inverter has a limit of 150% of its current rating for 1 min. Figure 5.14 illustrates the maximum torque (breakdown torque) capabilities of a 10-hp, four-pole induction motor under various voltage and current conditions. The maximum torque at 150% of motor rated current requires voltage boosts below 10 Hz, with the percent of voltage boost increasing as the frequency is decreased. The motor and adjustable-frequency power supply cannot operate continuously at these values of torques and current. These torques are important, however, when determining the acceleration time for high-inertia loads since the 150% current can be maintained only by the adjustable-frequency power supply for about 60 sec.

The locked-rotor torque or breakaway torque is a function of both the voltage and frequency applied to the motor. The locked-rotor torque per ampere increases as the frequency decreases, and the voltage is at constant volts/hertz down to about 6 Hz. The stator

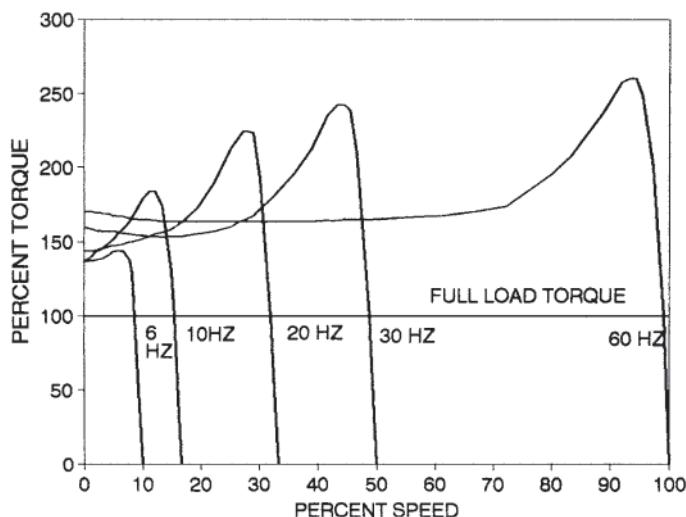


FIGURE 5.13 Speed-torque curves at constant volts/hertz for 100-hp, 1800-rpm, energy-efficient induction motor.

resistance may limit the torque that the motor develops at 6 Hz and lower. Figure 5.15 illustrates the low-frequency locked-rotor performance for a 10-hp, four-pole induction motor as a function of frequency and applied voltage. Locked-torque values at locked current equal to full-load current are shown by curve 2, Fig. 5.15. The voltages to achieve these values of torque are shown by curve 3, Fig. 5.15. This represents considerable voltage boost below about 3 Hz. Curve 4, Fig. 5.15, illustrates the voltage boost required to obtain locked torque equal to full-load torque. This indicates that locked torque equal to full-load torque can be obtained at rated voltage at about 6 Hz.

The actual value of locked-rotor torque or breakaway torque available depends on the motor characteristics and on the voltage boost capability of the adjustable-frequency power supply.

The starting torque and acceleration torque requirements may be a consideration, depending on the type of load and the inertia of the connected load. For most pumps and fans, this is usually not a

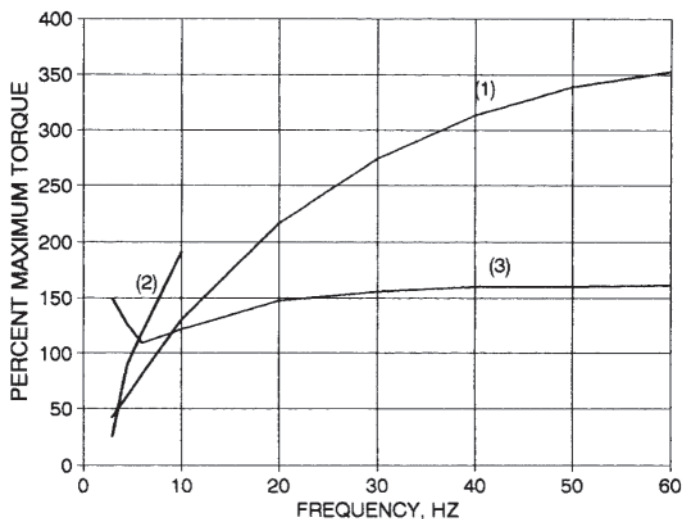


FIGURE 5.14 Maximum torque (BDT) for a 10-hp, four-pole induction motor. (1) Maximum torque (BDT) at constant volts/hertz. (2) Maximum torque (BDT) with 20% voltage boost. (3) Maximum torque (BDT) at 150% rated current (with voltage boost below 10 Hz).

problem. However, for a large fan with high inertia or other types of loads with high inertia such as a large flywheel, the time to accelerate the load becomes important. This time to accelerate the load can be expressed as

$$t = \frac{WK^2 \times \text{RPM}}{308 \times T}$$

where

t = time to accelerate, sec

WK^2 = moment of inertia of load referred to the motor plus the motor inertia, lb-ft²

RPM = change in speed, i.e., low speed to high speed

T = net accelerating torque

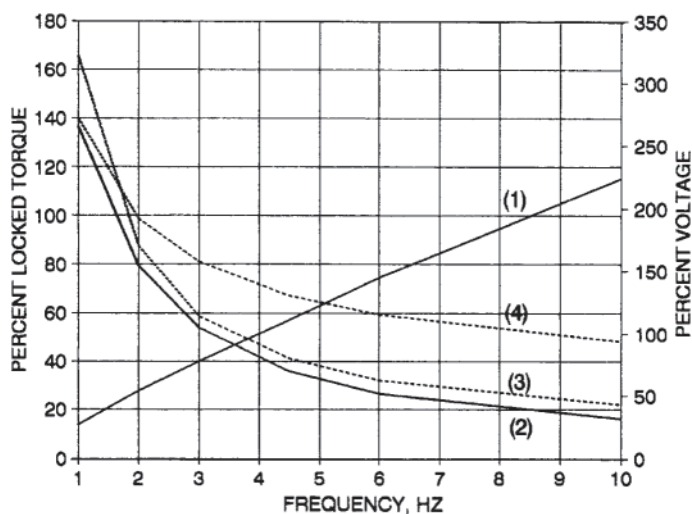


FIGURE 5.15 Locked-rotor performance at low frequencies for a 10-hp, four-pole, 60-Hz induction motor. (1) Percent locked torque at constant volts/hertz. (2) Percent locked torque at locked current equal to full-load current. (3) Percent voltage for locked current equal to full-load voltage. (4) Percent voltage for locked torque equal to full-load torque.

The net accelerating torque is the difference between the motor torque available and the torque required to drive the load. The motor torque available is a function of the voltage and current limitations imposed on the motor by the adjustable-frequency power supply. Therefore, the combination of the motor and adjustable-frequency power supply must be selected so that the load can be accelerated within the current-time constraint of the power supply and the acceleration time required for the application.

Induction Motor Efficiency. The efficiency of polyphase induction motors at constant-torque loads decreases as the frequency is decreased with constant-volt/hertz input. Figure 5.16 illustrates the efficiency of a 100-hp, 1800-rpm standard induction motor at various

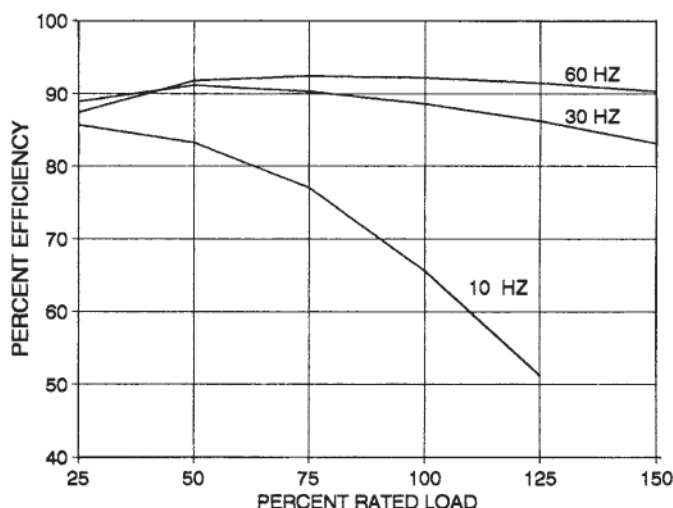


FIGURE 5.16 Efficiency of 100-hp, 1800-rpm standard motor at constant volts/hertz, sine power.

loads and frequencies when operated from a sine-wave power source. Similarly, Fig. 5.17 illustrates the performance of a 100-hp, 1800-rpm energy-efficient induction motor at various loads and frequencies when operated from a sine-wave power source.

Note that the energy-efficient motor has higher efficiency at all loads and frequencies and that this difference becomes more significant as the frequency is decreased. When the power source to the induction motor is nonsinusoidal and contains harmonics, additional losses, particularly stator and rotor winding losses and stray losses, are generated in the induction motor. The magnitude of the increased losses depends on the harmonic frequencies and voltages in the power source and also on the induction motor design.

Generally, the energy-efficient types of polyphase induction motors have a smaller increase in harmonic losses than the standard induction motors because of their lower stator and rotor resistances. Induction motors with deep-bar or T-bar rotors have higher

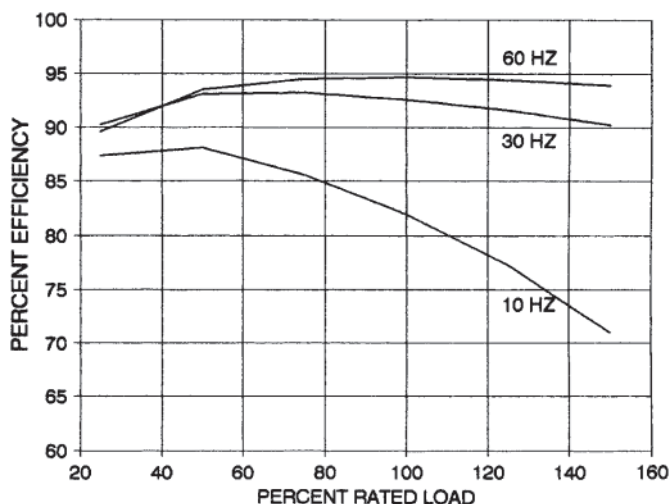


FIGURE 5.17 Efficiency of 100-hp, 1800-rpm energy-efficient motor at constant volts/hertz, sine power.

harmonic losses than induction motors with shallow-bar rotors. Induction motors with double-cage rotor construction can have excessive harmonic losses.

Figures 5.18 and 5.19 illustrate the increases in losses or decrease in efficiency for a particular motor/adjustable-power supply combination. There are no typical values for the increase in losses due to the harmonics since the increase depends on the magnitude and frequency of the harmonics generated by the adjustable-frequency power supply and the motor reaction to these harmonics. The increase in losses can range from as low as 10% to over 50%. Figure 5.20 shows a comparison of the efficiencies of a 100-hp, 1800-rpm standard motor and a 100-hp energy-efficient motor when supplied by a non-sine power source. Note the superior performance of the energy-efficient motor.

The six-step type of adjustable-frequency power supply generally causes a larger increase in induction motor losses than the pulse width modulation adjustable-frequency power supply.

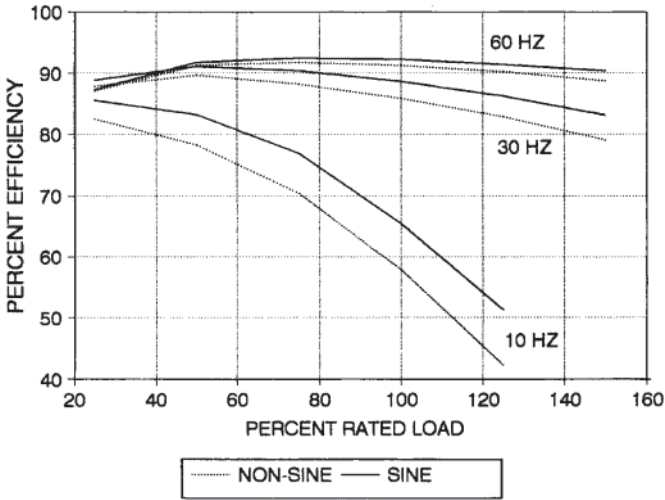


FIGURE 5.18 Comparison of a 100-hp, 1800-rpm standard motor efficiency with a sine-wave and a non-sine-wave power source.

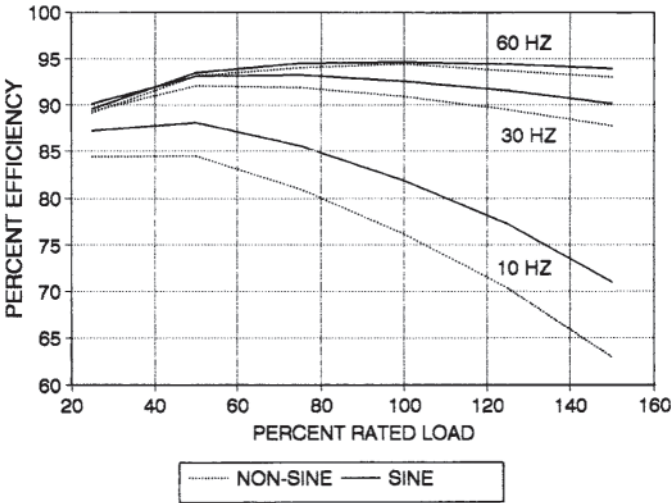


FIGURE 5.19 Comparison of a 100-hp, 1800-rpm energy-efficient motor efficiency with a sine-wave and a non-sine-wave power source.

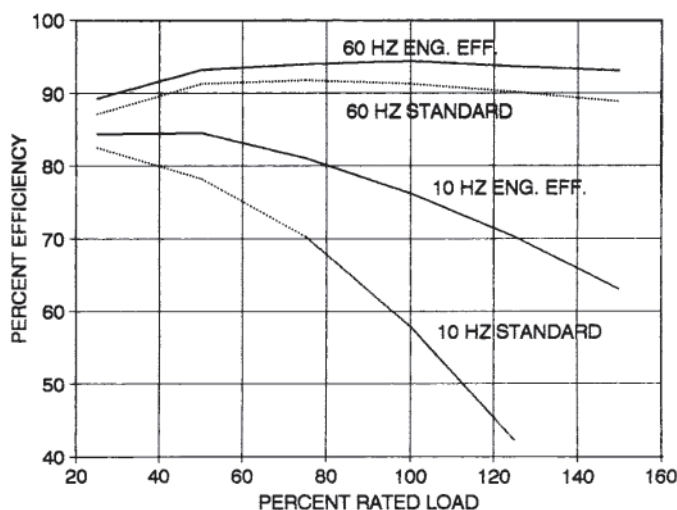


FIGURE 5.20 Efficiency comparison of a 100-hp, 1800-rpm energy-efficient motor versus a 100-hp, 1800-rpm standard motor, both with non-sine power.

Induction Motor Thermal Capacity. The induction motor nameplate identifies the type of motor enclosure, class of insulation, and service factor that the motor is rated for. These features determine the thermal capability of the motor. However, this rating is based on a sine power supply at rated voltage and frequency.

The heat dissipation of an induction motor depends on the class of insulation used in the motor, allowable temperature rise, ventilation, and type of enclosure. This varies from one motor manufacturer to another. However, in general, the allowable heat dissipation relative to the base-speed (60-Hz) heat dissipation decreases with speed (frequency) as shown in Fig. 5.21. Note that the heat-dissipation ability of the totally enclosed fan-cooled (TEFC) motor does not decrease as fast as that of the open motor. This is due to the ability of the TEFC to dissipate more of the heat generated by radiation and natural convection when operating at low speeds. The final temperature rise of the motor depends on heat-producing losses that must be dissipated, which are a function of the load,

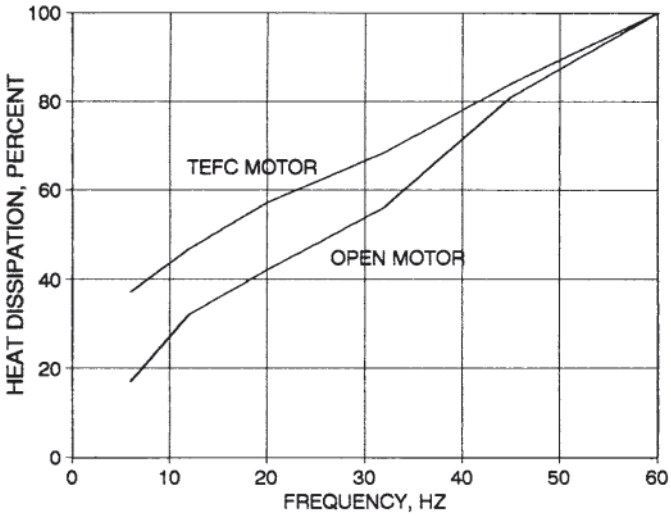


FIGURE 5.21 Relative heat-dissipation ability as a function of motor frequency (speed).

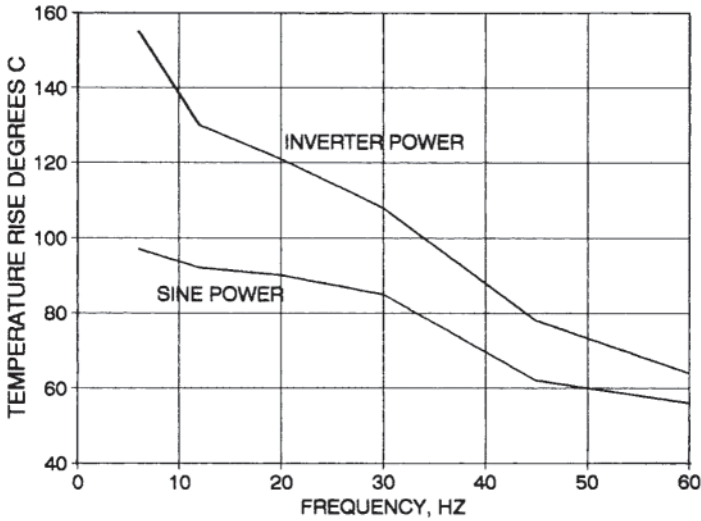


FIGURE 5.22 Temperature rise for a 5-hp, 1800-rpm open motor operating on a sine-wave power source versus an inverter power source.

speed, and harmonic losses caused by the motor input voltage. Again, the six-step adjustable-frequency power supply produces higher harmonic losses in the motor than the pulse width modulation power supply and results in higher motor temperatures.

The operation of a 5-hp, open, 1800-rpm induction motor on sine power supply and on an inverter with non-sine power supply are compared in Fig. 5.22. This figure compares the temperature rise for the same output torque at each frequency. The load was constant down to 30 Hz and was reduced at 20 Hz and lower to obtain constant temperature rise on the tests with the inverter power supply.

5.6.3 Summary: Induction Motor Selection for Adjustable-Frequency Inverter Systems

1. Define the load characteristics:
 - a. Starting or breakaway torque required
 - b. Type of load, i.e., variable torque, constant torque, constant horsepower, or cyclical
 - c. Base horsepower
 - d. Speed range for continuous operation
 - e. Acceleration time and load inertia
2. Define the type of adjustable-frequency inverter.
3. Determine the motor horsepower rating and derating based on the torque requirements, speed range, and thermal capacity, considering the constraints imposed on the motor by the adjustable-frequency inverter.